

The information paradox¹

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Los muertos que vos matasteis gozan de buena salud²

Abstract

The incompatibility between gravity and quantum coherence represented by black holes should be solved by a consistent quantum theory that contains gravity as superstring theory. Despite many encouraging results in that sense, I question here the general feeling of a naïve resolution of the paradox. And indicate non trivial physical possibilities towards its solution that are suggested by string theory and may be further investigated in its context.

1 Introduction

The fact that black holes represent an apparent contradiction between gravity and quantum mechanics is a too well known problem to need exhaustive recall. The best way to visualize it is to consider together the formation and evaporation processes. We may envisage a b.h. to be formed by a pure quantum state prepared in a distant flat space (an impinging spherical wave, two or 25 particles colliding at high energies and small impact parameter, and so on). If the characteristics of a b.h. — including its evaporation implied by quantum mechanics — depend only on few basic parameters (M , Q , J) as required by general relativity (no hairs), it is clear that quantum coherence of the initial state is totally lost in the process. The contradiction has resisted efforts to doctored modifications (as corrections to the thermal character of Hawking evaporation) and brought distinguished scientists to give up either quantum mechanics [1] or the relevance of classical (general relativity) solutions in a path integral formulation of the quantum theory of gravitation [2].

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² Jose’ Zorrilla, “Don Juan Tenorio” (1844).

On the other hand, the advent of string (actually superstring) theory as a consistent quantum theory that contains gravity gave confidence that somehow the paradox should be solved in its framework. Much progress has been done in studying b.h. regimes in string theories and a remarkable set of coincidences have been revealed. After briefly recalling those results, I will argue that the paradox not only isn't trivially solved as often claimed, but manifests its full vitality in compelling some quite novel possibilities in the generalization to the quantum realm of some classical concepts as space-time and its geometry, or the influence that quantum effects may have on the actual realization of classical geometrical configurations as trapped space-time regions.

2 String theories and black holes

String theories contain arbitrarily massive states within regions characterized by the string length l_s — the basic dimensional parameter of the theory — thus states that, classically, would represent black holes. The mass beyond which those states should be black holes, depends [3] on the string coupling g , the other — dimensionless — basic parameter of the theory. Or in different words, for every mass (or excitation energy) there is a small coupling string regime, and a large coupling b.h. regime.

In the string regime, D-branes in four [4] and five [5] dimensions with a convenient number of charges have been studied. BPS states have been counted as well as nearly BPS states for certain regions of moduli space where perturbative computations are feasible [6]. Decay rates have been computed [7] — by averaging over the many degenerate initial states — and shown to have a typical thermal distribution. The moduli independence of these results allows to conjecture [8] their validity beyond the moduli region where they were computed. And their g independence, also suggested by non-renormalization arguments [9], may imply their possible continuation beyond the weak coupling regime.

An independent treatment — on totally different grounds — of the strong coupling regime substantiates that impression. The large g description of the 4 and 5 dimensional systems just described is found by solving the 10-d supergravity equations after reduction on the same compact manifold used for the D-brane description. The solution generates a metric [10] that depends on parameters that are related to the charges through the moduli of the compact manifold. The metric shows an event horizon even in the extreme limit in which its area gives the Bekenstein-Hawking entropy of extremal b.h.. This entropy and the ADM mass coincide with the (exponentiated) multiplicity and mass of the BPS states with the same charges as computed from the D-branes in the small coupling regime. For nearly extremal b.h. the entropy and the evaporation spectrum — obtained by solving wave equations in the corresponding metric background — coincide again [7] with those computed

for small g . And, remarkably, even deviations from black body spectrum seem to agree [11].

The microscopic formulation of the 5-d near extremal b.h. has been further studied [12] in terms of the D1-D5 brane system. The AdS/ CFT correspondence was shown to play a role in the matching between supergravity results and the microscopic (SCFT) formulation of the b.h. thermodynamics and Hawking radiation, the b.h. being defined through a density matrix.

All these agreements among such different computations gave confidence to the g continuation of the theory to a strong coupling regime where b.h. physics is met. This direct connection between the semiclassical black hole picture and a unitary quantum approach, has been considered the sign that the information loss due to b.h. could be somehow recuperated [13]. But how this may be achieved is yet far from clear. In the computations just referred it appeared clearly that the thermal Hawking radiation was obtained by the averaging over the degenerate microstates that are counted by the b.h. entropy, while each microstate would have given rise to a complex but non thermal radiation with well defined spectra and correlations that carry the precise identity of the microstate from which they would have been originated. This is of course a basic characteristics of a microstate (a pure quantum state) irrespectively of g . In other words, the black hole microstates are not themselves black holes [14]. And this not only because of the absolute specificity of its radiation, but also by not having any signal of an event horizon associated with each of them. This last fact is of course expected by sheer consistency: if a b.h. microstate would be characterized by an event horizon, it would have — itself — a Bekenstein entropy and thus would not be a pure quantum state. The b.h. appears indeed as the macrostate correctly defined by a decoherence procedure — density matrix — over the many non-blackholish microstates of the theory [15].

The obvious consequence of the preceding discussion is that a well prepared quantum state (a spherical shell impinging from large distances, or a two particle scattering at high energy and small impact parameter, etc.) is not expected to give rise to a b.h. even if the classical conditions for a gravitational collapse are apparently satisfied.

The possibility that microstates do not have a horizon has been more recently proposed in a different context [13]: for every wrapping of a D-1 brane (whose number defines one of the charges briefly mentioned before) a profile function in transverse space is introduced so to enter into a momentum charge that contributes to the BPS charge. These profile functions then enter into the supergravity solutions that are supposed to hold in the strong coupling regime and change their behaviour at short radius, differently for every different profile function. They are not singular at $r=0$ and the value of r where they all start resembling the usual b.h. solution outside the horizon is identified as a fuzzy “horizon” of a fuzzball proposal for b.h.. It is unclear, however, if and how a trapped region could emerge for the incoherent superposition characterizing the b.h. macrostate.

3 The role of decoherence

If string microstates counted by the entropy of b.h. macrostates are not themselves black holes, it should happen that decoherence, intrinsic to any classical limit, should be critical in building b.h. characteristics as metric singularities and event horizons. It is not surprising that decoherence may have an important role in high excitation string physics due to the very large degeneracy of states in that regime. Indeed, even for $g \rightarrow 0$, i.e. tree diagrams, the non-trivial spectrum of emitted particles in the decay of any high mass excitation gives rise to a thermal distribution if an average over the very many states with the same mass is performed [16].

Even if effects of this kind may well be at work also for large couplings, decoherence should have much more subtle effects in order to generate b.h. physics from non black-holish microstates. Let me provide some speculative ideas on how a geometric picture could arise from a decoherence procedure in the pregeometric string approach. In this theory, indeed, even space and time are defined through the string; they are operators and not parameters that could be interpreted as coordinates of a space-time that may subtend a dynamical geometry. These are all concepts that may arise in a classical limit of the theory when quantum fluctuations may be neglected. But even in this limit, the theory contains in principle not only the metric and possibly matter fields, but also an infinite number of higher tensor fields whose effect may possibly be ignored only in some conditions. The (infinite number of) equations that these (infinite number of) fields should satisfy, are given by the condition of no conformal anomaly ($\beta = 0$), and it is in the limit of small frequencies (in string length units) that only massless fields appear satisfying Einstein's equations [17]. But in presence of a horizon of a metric solution, the statement of low frequency is not relativistic invariant. Indeed, an arbitrary low frequency wave for a fixed external observer will be perceived by a free falling one with a blue shift which gets arbitrarily increased when approaching the horizon. This means that to have disregarded contributions with higher derivatives, or fields with higher tensorial character, would have been an unwarranted approximation. And even a small effect of those tensors could have avoided the metric condition that implied the singularity and the trapped region in the usual Einstein equation. There could be many solutions involving different field configurations in which the metric and other tensor fields are classically entangled with relevant phases. And it could well happen that an incoherent superposition of these different background configurations could wash out the higher tensorial fields leaving a geometric description with, eventually, a b.h. metric with its singularity and its event horizon. This could be a hypothetical way in which non b.h. microstates could give rise to a b.h. macrostate.

In this case, the apparent contradiction between b.h. in classical general relativity and quantum coherence is solved in a conceptually simple way: it is the decoherence procedure, implied in any classical limit, that gives rise

— from a consistent quantum theory of gravitation as superstrings — to a classical geometrical space-time description (general relativity) with eventual trapped regions, event horizon and b.h. and, of course, the loss of quantum coherence.

4 High energy collisions in string theory and metric back reaction

Let us now discuss high energy scattering. Superstrings provide a computational perturbative algorithm for S-matrix amplitudes that, if properly resummed, allows an explicit analysis of the continuation to the strong coupling (b.h.) regime. Therefore, as we shall discuss later, the consistent quantum theory may investigate situations in which, semiclassically, the process should be described by a b.h. formation and subsequent evaporation. Thus, hopefully, the analysis may throw light on how and why may happen that a coherent quantum state would not produce a b.h. even if the classical conditions to form it are met.

Much work has been done to study trans-Planckian collisions in a string approach [18,19]. I will recall methods and results that are consistently computable in the string regime and organized in an effective action form [20] to tackle their extension to a strong coupling regime where, semiclassically, b.h. formation and subsequent evaporation should be expected. As already said, string (or actually superstring) theories contain a dimensional scale — the string length l_s — and a dimensionless one g , the string coupling that generates the genus expansion. Gravitational scales, as the Newton constant G or the Schwarzschild radius R_S corresponding to an energy E are given by

$$G = g^2 l_s^2 / \hbar \qquad R_S = GE \qquad (1)$$

For simplicity, eqs (1) and other explicit expressions we shall give refer to the $d = 4$ case even if the analysis we recall has been done for arbitrary d non compactified dimensions. The method used in refs.[18] is to consider a trans-Planckian regime defined by a small coupling-large energy

$$g^2 \ll l, El_s / \hbar \gg 1 \qquad (2)$$

so that

$$GE^2 / \hbar = g^2 (El_s / \hbar)^2 > 1 \qquad (3)$$

In the genus expansion of string amplitudes all terms in which g^2 is enhanced by the large factor as in eq. (3) have to be considered and resummed. Let us notice that in the large energy regime of eqs. (2), (3) $R_S / l_s = g^2 El_s / \hbar$ can be smaller or larger than one and, as we shall see, physics will be different on the two sides of the inequality. The computation of the collision amplitude in superstring theory in terms of the energy E and impact parameter b has

been organized in powers of R_S^2/b^2 . For b larger than both R_S and l_s , the two particle collision amplitude in the high energy regime as defined by eq. (2) — obtained by the just discussed all order resummation — has an eikonal form, the eikonal being a Hermitian operator (thus unitary S-matrix) in the Fock space of the two colliding strings. Only for very large values of b — where the amplitude is perturbative and dominated by the graviton pole — the scattering is elastic, while for $b < gEl_s^2/\hbar$ the two colliding gravitons are also excited to other superstring states in the scattering process. The eikonal is large and allows a classical trajectory interpretation through a saddle point in the Bessel transform to transfer momentum. It reproduces the relation between deflection angle and impact parameter classically experienced by each particle in the gravitational field (Aichelburg-Sexl) created by the other one. With the extra fact that while deflecting, colliding particles may be excited (in a calculable way) to one of its string recurrences, implying an attenuation of the elastic amplitude (imaginary phase) that increases, together with the deflection angle, for decreasing b . In the $R_S < l_s$ case, b may decrease where string effects become relevant, giving rise to copious inelastic production [21] and thus a softening that implies an attenuation of the elastic amplitude and a reduced deflection angle. In the $R_S > l_s$ case, when b approaches R_S new terms appear, as said before, in the form of powers of R_S^2/b^2 that look as classical corrections despite their quantum origin. The first term has been computed in the string framework [15, 22] and an effective action algorithm has been proposed for computing and resumming them all [20]. This may be interpreted as a metric and dilaton background generated by the process or, equivalently, a consistent quantum computation of back reaction on the metric, giving effects that become relevant when approaching situations in which a b.h formation is classically expected. It could thus represent a way of understanding how and why a b.h. is avoided in a well defined quantum state as that under discussion. It is perhaps unfortunate that no further effort has been devoted in that direction. I have even a vague recall of a sense of frustration of the scientist to whom we dedicate these contributions, Ciafaloni and myself when — many years ago — some preliminary results could not be forced into the recognition of a horizon. Fact that brought us to give up, while today I would consider it as the expected sign to reveal novel quantum gravitational effects! Furthermore, if this sort of back reaction is efficient in avoiding trapped regions in the well defined quantum state represented by the two colliding particles, it could perhaps continue to do so in arbitrary collapse situations. Let me also adventure that this possible effect of quantum back reactions on the metric may allow an interpretation of the recent Hawking suggestion [2] that the original classical solution, as the Schwarzschild metric in a gravitational collapse, may give an irrelevant contribution to the path integral for the actual gravitational process.

5 Metric back reaction and possible avoidance of blackholes

The idea that that standard b.h. may not be the objects realized in nature even at the macroscopic level, has been recently explored within different contexts [23]. In particular, interesting suggestions have been borrowed from geometric acoustical models that can be studied experimentally and show a physics that is associated with classical and quantum fields in curved space-times [24]. Propagation of small disturbances in the flow of even simple fluids are known to behave equivalently to a linear (classical or quantum) field over an acoustic space-time endowed with an acoustic metric [25]. Depending on that endowed metric, acoustic b.h. -trapped region corresponding to a supersonic regime in fluid flow- may be created. It has been however noted [26] that Hawking-like radiation does not necessarily imply the formation of a trapped region; it is sufficient that a sonic point conveniently develops in the asymptotic future. The radiation is then controlled by a temperature that contains both the Hawking one and the rate by which the sonic point is reached for $t \rightarrow \infty$. This critical collapse result suggests an alternative scenario for a semiclassical collapse and evaporation of “b.h.” objects that — very speculatively — could be exported to semiclassical gravity. Its interpretation would imply that some quantum back-reaction on the geometry could prevent the surface of the collapsing star (or impinging matter) from actually crossing the Schwarzschild radius. At later stages, the evaporation process would become more efficient so to induce a chasing of the would be horizon by the surface of the star that could end with the complete evaporation and a flat space-time [26].

6 Conclusions and outlook

I hope to have substantiated my (probably personal) point of view of why some coincidences between string state multiplicity and average decay spectra, on one hand, and b.h. entropy and evaporation spectra, on the other, are far from having solved in a naive way the apparent paradox of loss of quantum coherence in b.h. formation and evaporation (the information paradox). String microstates, in particular, aren’t b.h. and well defined quantum states would not generate b.h. even if they would have been expected on classical grounds. I have discussed two ways to resolve this apparent discrepancy, both of them accessible to further investigation in the string framework. The first one starts from the fact that superstring theory is pregeometrical and even the concept of space-time is induced by the string through a classical limit. Thus space-time, geometry, event horizons, black holes and the loss of quantum coherence would all come with the same token i.e. the decoherence procedure implied in the classical limit that leads to general relativity. Thus no paradox: either bona fide quantum (as superstrings) or classical space-time with

dynamical geometry and black holes but no a priori quantum coherence. The other possibility is that the lack of b.h. formation in a quantum state, as two particle collision, may be due to well identified quantum contributions that give rise to apparently classical effects that act as quantum back reactions on the metric. Effects that could remain influential even in classical gravitational collapse processes thus avoiding metric singularities, trapped regions and event horizons. Without forming, therefore, even classical b.h. despite the fact that many external observational properties would not look very dissimilar. Thus no paradox because no real black holes: no trapped region or event horizon to spoil quantum coherence or information retrieval.

Recognition

I had the chance to enjoy a lively and fruitful collaboration with Gabriele for many years and on a variety of subjects. Sharing — as also reflected in this paper — the joy of elaborating original physics, the frustration of unexpected obstacles and the persisting challenge of different viewpoints on possible developments. I wish him to keep harvesting success, surrounded by friends and collaborators attracted by his scientific and human qualities. People of all origins and ages..... with me at the oldest end.

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